PB85-247005

Preliminary Evaluation of a Modified NBS PM(10) Sampler for Indoor Particulate Measurements

Environmental Monitoring and Services, Inc.
Newbury Park, CA

Prepared for

Environmental Monitoring Systems Lab.
Research Triangle Park, NC

Aug 85

U.S. Department of Commerce
National Technical Information Service
NTIS

EPA/600/4-85/057
August 1985

PB85-247005

PRELIMINARY EVALUATION OF A MODIFIED NBS PM10 SAMPLER FOR INDOOR PARTICULATE MEASUREMENTS

by

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U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/4-85/057	2.	3. RECIPIENT'S ACCESSION NO. PB85 247005 7AS
4. TITLE AND SUBTITLE Preliminary Evaluation of a Modified NBS PM_{10} Sampler for Indoor Particulate Measurements		5. REPORT DATE August 1985 6. PERFORMING ORGANIZATION CODE MAD
7. AUTHOR(S) J. E. Howes, Jr., R. Vijayakumar, F. Doerfler, F. J. Burmann, F. S. Howard		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Monitoring and Services, Inc. Newbury Park, CA 91320 Esoteric Systems, Inc, Newbury Park, CA		10. PROGRAM ELEMENT NO. A119 11. CONTRACT/GRANT NO. 68-02-4084
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Protection Agency Environmental Monitoring Systems Laboratory Research Triangle Park, N.C.		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/08
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

Modifications have been made in the prototype NBS portable sampler to overcome several design flaws. The modifications included replacement of the case, redesign of the filter holder, and addition of a motor control circuit. Results obtained in a brief performance evaluation indicate that the modified sampler yields PM_{10} data comparable to that obtained with a conventional ambient-type dichotomous sampler.

The battery pack (six 1.25V Ni-Cd D cells) used with the modified NBS sampler provides at least 24 hours of operation at a flow rate of 6 lpm. The constant current motor control circuit added to the sampler provides a very uniform flow rate (within ±5%) over a 24-hour sampling period. The circuit also automatically decouples the motor when the battery output drops below a voltage that delivers a flow rate of 6 lpm.

The performance of an indoor air sampler developed by Harvard University was also evaluated in this study. The mean difference between results obtained with collocated pairs of the Harvard and conventional dichotomous samplers during nine days of sampling was less than 2%. The range of differences in PM_{10} mass concentration for the nine comparisons was 13.7 to -14.3%. The results obtained with the Harvard sampler exhibit excellent agreement with the dichotomous data considering the weighing errors associated with the measurements and the possible inhomogeneity of particles in test atmosphere.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 39
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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FORWARD

Measurement and monitoring research efforts are designed to anticipate potential environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations, and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Environmental Monitoring Systems Laboratory, Research Triangle Park, North Carolina, has the responsibility for: assessment of environmental monitoring technology and systems; implementation of agency-wide quality assurance programs for air pollution measurement systems; and supplying technical support to other groups in the Agency including the Office of Air, Noise and Radiation, the Office of Toxic Substances and the Office of Enforcement.

This document is a report on the evaluation of personal exposure instrumentation for PM_{10} particulate matter. The report specifies improvements in the instrumentation and presents preliminary results of applying the improvements to field sampling.

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ABSTRACT

Modifications have been made in the prototype NBS portable sampler to overcome several design flaws. The modifications included replacement of the case, redesign of the filter holder, and addition of a motor control circuit. Results obtained in a brief performance evaluation indicate that the modified sampler yields PM_{10} data comparable to that obtained with a conventional ambient-type dichotomous sampler. However, several additional modifications and improvements are needed and further field testing of the unit is required to produce a field-worthy personal version.

The weakest component of the current version of the NBS sampler is the pump/motor assembly. In this application, the Sensidyne (formerly Bendix) unit has an unacceptably short pump/motor lifetime and an unfavorable flow rate-pressure drop relationship. Replacement of the pump/motor assembly is recommended if a suitable candidate unit can be identified.

The battery pack (six 1.25V Ni-Cd D cells) used with the modified NBS sampler provides at least 24 hours of operation at a flow rate of 6 lpm. The constant current motor control circuit added to the sampler provides a very uniform flow rate (within $\pm$5 percent) over a 24-hour sampling period. The circuit also automatically decouples the motor when the battery output drops below a voltage that delivers a flow rate of 6 lpm. In the NBS sampler, a Nuclepore filter in tandem with a Teflon filter is used to collect the coarse ($\sim$2.5 to 10 µm) and fine (0 to $\sim$2.5 µm) particulate matter, respectively. Elimination of the Nuclepore filter is recommended since its use may increase the error in the particulate measurements and it is questionable whether accurate particle size resolution is obtained. The Nuclepore filters are difficult to weigh due to buildup of static charge on the filters. In addition, distribution of the small total mass usually obtained in indoor environments between two filters compounds the weighing error. Use of the filter pack to distinguish size fractions yields only an approximate particle

size cut which has been found to be geometric rather than aerodynamic by John, et. al. (1).

Finally, the components of the NBS sampler must be packaged for personal sampling applications. The recommended configuration consists of an inlet/filter assembly which can be attached near the breathing zone and connected by a flexible sample line to the pump/battery/control unit(s) either worn on a belt or contained in a shoulder bag.

The performance of an indoor air sampler developed by Harvard University was also evaluated in this study. The mean difference between results obtained with collocated pairs of the Harvard and conventional dichotomous samplers during nine days of sampling was less than two percent. The range of differences in PM_{10} mass concentration for the nine comparisons was 13.7 to -14.3 percent. The results obtained with the Harvard sampler exhibit excellent agreement with the dichotomous data considering the weighing errors associated with the measurements and the possible inhomogeneity of particles in test atmosphere.

This report was submitted in partial fulfillment of Contract No. 68-02-4084 by Environmental Monitoring and Services, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from May 1984 to July 1985, and the work was completed as of July 1985.

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LIST OF ABBREVIATIONS

ABBREVIATIONS

lpm	-- liters per minute (25°C, 760 mm Hg)
$\mu g/m^3$	-- micrograms per cubic meter (25°C, 760 mm Hg)
μm	-- micrometer
mm	-- millimeter
cm	-- centimeter
m	-- meter
μg	-- microgram
ma	-- milliampere
V	-- volts
CmH_2O	-- centimeters of water
mmHg	-- millimeter of mercury
°C	-- degrees centigrade
PDT	-- Pacific daylight-savings time
SD	-- standard deviation
DCT	-- Sierra-Andersen Model 244 dichotomous sampler
EPA	-- U.S. Environmental Protection Agency
NBS	-- National Bureau of Standards

SECTION 1

INTRODUCTION

Increasing scientific evidence suggests that the greatest health risk is posed by the smaller particles which deposit within the human respiratory tract. In recognition of this fact the U.S. Environmental Protection Agency (EPA) has proposed PM_{10} regulations that would require monitoring and control of ambient particulate matter which is equal to or smaller than 10 μm in aerodynamic diameter. The equipment required to measure PM_{10} mass concentration levels in the ambient environment has been evaluated by EPA during the past three years (2). However, the ambient samplers because of size, noise, and other factors are too obtrusive for use in indoor environments.

To meet the requirements for indoor particulate monitoring, the EPA sponsored development of a portable PM_{10} sampler by the National Bureau of Standards (NBS). The design criteria adopted by NBS were as follows (3,4):

- The sampler should have well defined, stable cut points with respect to particle size.
- The samples (as with the standard EPA area samplers) should be collected on filters for subsequent weighing and chemical analysis.
- The sampler should have as high a sampling flow rate as possible since ambient particle concentrations are typically low and a $\geq$100 μg particle sample per filter is necessary for a gravimetric measurement uncertainty of $\leq$10 percent.
- X-ray fluorescence, a widely used method for elemental analysis of filter samples, requires the sample be in an even, homogeneous layer on the filter.
- To be acceptable to volunteers participating in exposure studies, the sampler must be light, quiet and inconspicuous.
- To be able to sample at high flow rates for long time periods and still be small and light weight, the sampler must have energy efficient components. This means that the sampler air path must have a low pressure drop and that the motor-pump unit have low internal frictional

losses.

Several prototype NBS samplers were constructed and evaluated by Research Triangle Institute (RTI) in previous field studies (5). The work described in the present report was undertaken to improve several weaknesses in the design of the prototype units identified by RTI in the earlier work. A second objective was to obtain performance data on the improved units. In addition, performance data were also obtained on the indoor sampler designed for the Harvard Multicities Study (6,7).

SECTION 2

CONCLUSIONS

The conclusions drawn from results of this study may be summarized as follows:

- This work and a previous field evaluation have disclosed several flaws in the design of the prototype NBS portable particulate sampler. The problems that have been identified include a) potentially inaccurate sampling rates due to susceptibility of the sampler case to leakage, b) susceptibility of the filter cassette to leakage and accidental disassembly if jarred or bumped, c) premature failure of the sampling pump unit, and d) possible movement of the inlet components (funnel insert and oil-soaked frit) thus changing the inlet cut point. Other features which may effect user acceptance of the NBS prototype sampler are the difficulty in changing filters due to inaccessibility of the filter cassette, poor weight distribution, and unsuitability of the sampler configuration for personal monitoring applications.

- A modified, portable version of the NBS sampler was assembled in this study with the objective of eliminating some of the shortcomings in the NBS design. A limited evaluation of the modified sampler has indicated that the weakest component in the system is the sampling pump. The Sensidyne (formerly Bendix) pump assembly used in the NBS design and the modified sampler has an unacceptably short lifetime (at least in this application); one new assembly failed after less than 100 hours of operation. The pump also has marginally acceptable flow characteristics for this application. The flow rate is very sensitive to pressure changes on the fore and backside of the pump. This poses a problem in performing flow calibrations on the sampler.

- Performance evaluation of the original design by NBS and evaluation of the modified version developed during this study shows that the sampler yields PM_{10} measurements (i.e. total mass concentration ≤ 10 µm) which are in reasonable agreement with collocated dichotomous sampler data. However, the results of this study suggest that there is some doubt regarding the ability and usefulness of the NBS sampler to resolve the distribution of particles within the 0 to 10 µm aerodynamic size range.

- The NBS and the modified units have demonstrated that battery lifetime will provide at least 24 hours of sampler operation. The motor control circuitry incorporated in the modified sampler will provide more uniform pump performance and longer sampler lifetime.

- Both the original and modified version of the NBS sampler use two

filters; an Apiezon-coated Nuclepore filter for collection of the ~2.5 to 10 μm size fraction and a Teflon filter for the 0 to ~2.5 μm size range. The errors associated with these respective measurements must be assessed. The results of this study indicate that resolution of the fine and coarse particle fractions may be impractical and that the general application of the NBS sampler should be directed toward determination of the mass of the particle size fraction $\leq$ 10 μm in aerodynamic diameter.

- In this study, the average of mass concentration measurements determined by collocated dichotomous and Harvard samplers agreed within 2 percent based on tests conducted over nine sampling periods (of at least 24 hours in duration).

SECTION 3

RECOMMENDATIONS

The preliminary evaluation of the NBS sampler and the modified, portable version developed in this study suggests the following recommendations:

- The most crucial issue in developing a field-worthy sampler is the pump reliability. Either the Sensidyne unit must be upgraded to provide reliable performance or an alternate pump must be identified.

- The resolution of the fine and coarse particle fractions using the Nuclepore/Teflon filter pack does not appear practical. It is recommended for routine applications that a single filter (2 or 3 μm pore size Teflon with polyolefin support ring) be used and that only the 0-10 μm size range be collected. This will also simplify the use of the sampler, provide more reliable data, and permit a further reduction in size.

- In this study, modifications were incorporated to construct and evaluate a portable version of the NBS sampler. Ultimately, a personal version of the sampler is required for indoor exposure studies. When final design criteria are set and reliable components are found, a personal version of the sampler can be constructed. It is recommended that configuration of the personal sampler should consist of an inlet that can be clipped on an individual's lapel or shirt pocket connected by a flexible line to a pump unit either worn on a belt or in soft case, e.g. camera bag with a shoulder strap. Consideration should be given to further size reduction of the inlet assembly so that it is relatively unobtrusive when clipped to a lapel or pocket.

- Additional laboratory and field testing will be required to demonstrate the field-worthiness of the final NBS sampler design. Further field testing of both the NBS and Harvard units is recommended to evaluate their performance under a wider range of particulate mass concentration and environmental conditions.

It may also be useful to explore sampler modifications for alternate flow rates rather than 6 lpm. Then, it would be possible to develop a personal sampler based on the availability of pumps and motors rather than being forced to select hardware from a limited choice that meets the design requirements.

SECTION 4

SAMPLER MODIFICATIONS/IMPROVEMENTS

NBS PORTABLE AMBIENT AEROSOL SAMPLER

The major effort in this program involved evaluating the NBS sampler and its component parts and making design changes to overcome deficiencies that were found. The following sections describe characterization and evaluation of the sampler components and design modifications that were made.

Sampler Case

In the NBS sampler design, the case functions as a chamber to dampen the flow pulsation of the pump. The case is highly susceptible to leakage which causes inaccuracies in the sampling rate. As a modification for this study, a moulded fiberglass, weather-proof electrical box* was used to contain the pump and provide pulse dampening. The box size which was approximately 18 x 15 x 7.6 cm also provide space for the battery pack. It was discovered that the fiberglass case provided significantly more reduction in the pump noise level than did metal cases.

The case and sampler configuration used in the modification are acceptable as a portable indoor area monitor but unsuitable for personal monitoring. For a personal version of the sampler, a smaller case can be used for the pump and batteries, and the inlet/filter assembly can be attached by means of a flexible sampling line.

Sampling Pump

A Sensidyne (formerly Bendix) Model BDX 30 pump is used in the NBS sampler. The motor/pump unit is relatively efficient in that a battery pack consisting of

* Purchased from Robroy Industries, 500 Maple St., Belding, MI 48809

six Ni-Cd D cells provides at least 24 hours of operation per battery charge. However, the pump has several deficiencies that limit the performance of the sampler. The most serious problem is the short lifetime of the pump/motor assembly. NBS reports consistent failure of the pumps after 800 to 1000 hours of operation. Failure of two pump motors occurred during this work; one after <100 hours of use. Discussions with Sensidyne personnel have confirmed that a significant reduction in the lifetime can be expected since in this application the unit is being operated at over twice the design flow rate.

Another problem is that when operated at 6 lpm the flow rate of the pump is highly dependent on differential pressure as shown in Figure 1. Thus, significant flow rate changes may occur with loading of the filters. Also, this characteristic introduces a calibration problem since connection of an external flow calibration device changes the pump loading (DP) and, thus, the flow rate. For this work, the problem was eliminated by permanently connecting a calibrated rotameter to the pump outlet to measure the flow.

The performance of the Sensidyne pump assembly over an extended time period is shown in Figure 2. The differential pressure curve indicates that a significant change in flow rate may occur over the first 5 hours of operation. In order to stabilize the pump performance, the motor control circuit shown in Figure 3 was incorporated into the sampler. Table 1 shows the flow performance of the sampler with the motor control circuit installed. The data show that the circuit stabilizes the flow rate by providing constant current to the motor. A uniform flow rate of 6 lpm ($\pm$5 percent) was measured in three 24-hour tests including the one shown in the table. An auto-shutdown feature is included which disengages the motor when the battery output drops below the voltage (~5 V) that will provide a 6 lpm flow rate.

Filter Holder

Millipore plastic filter holders are used in the NBS sampler design. The restricted accessibility of the filter holders make changing the filters

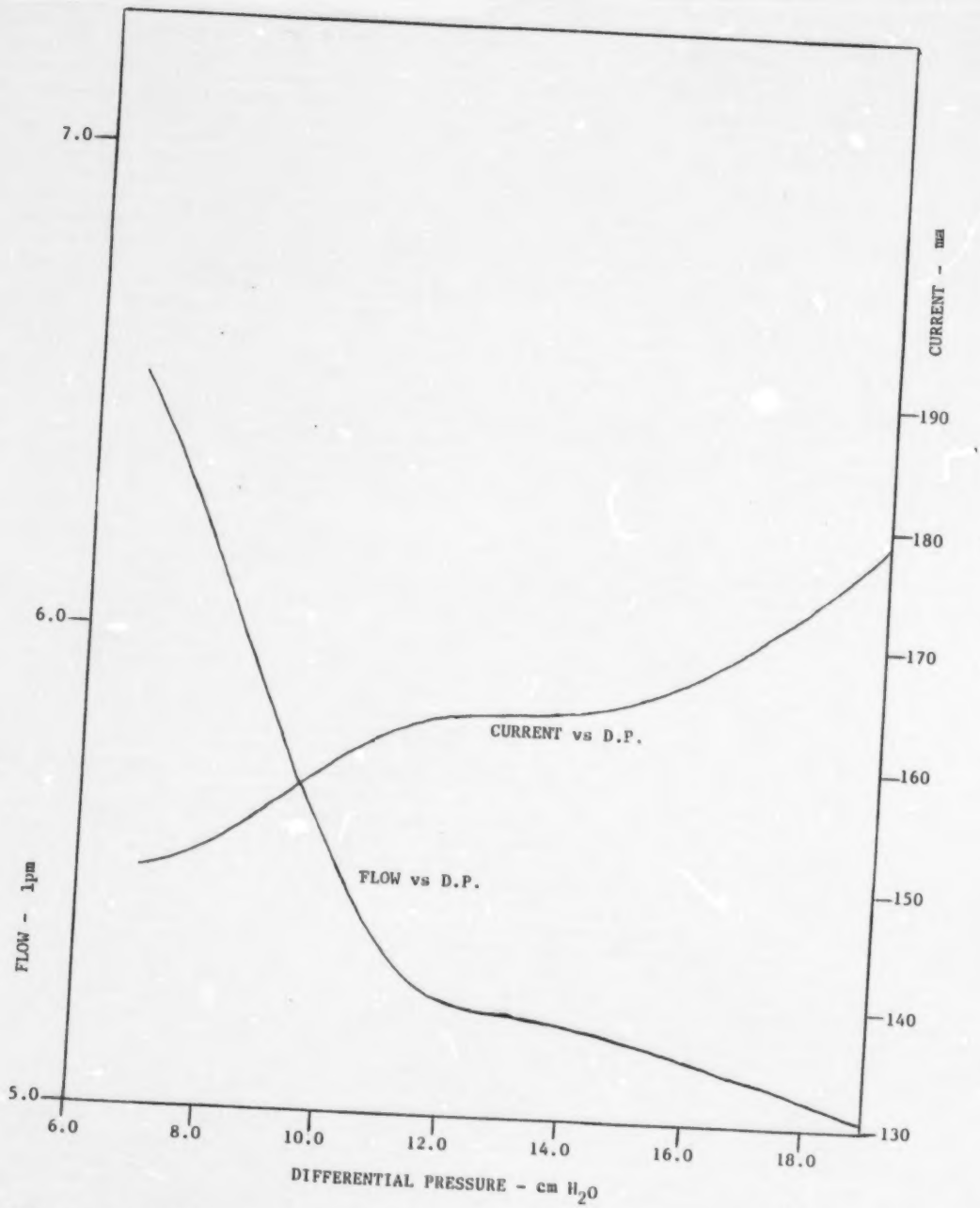


Figure 1. Pump characteristics as a function of differential pressure loading. (Test performed at a constant voltage of 6.45v)

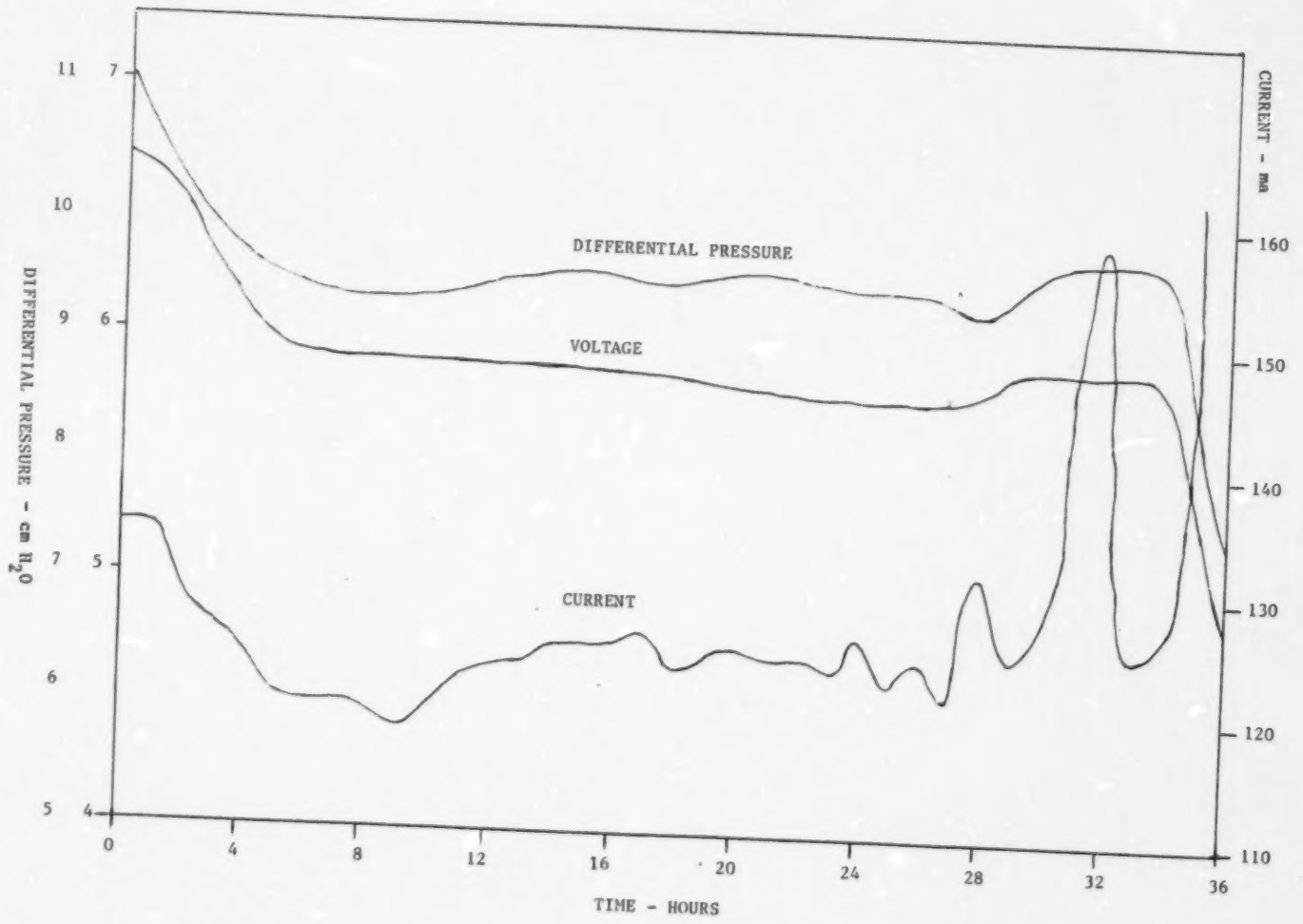
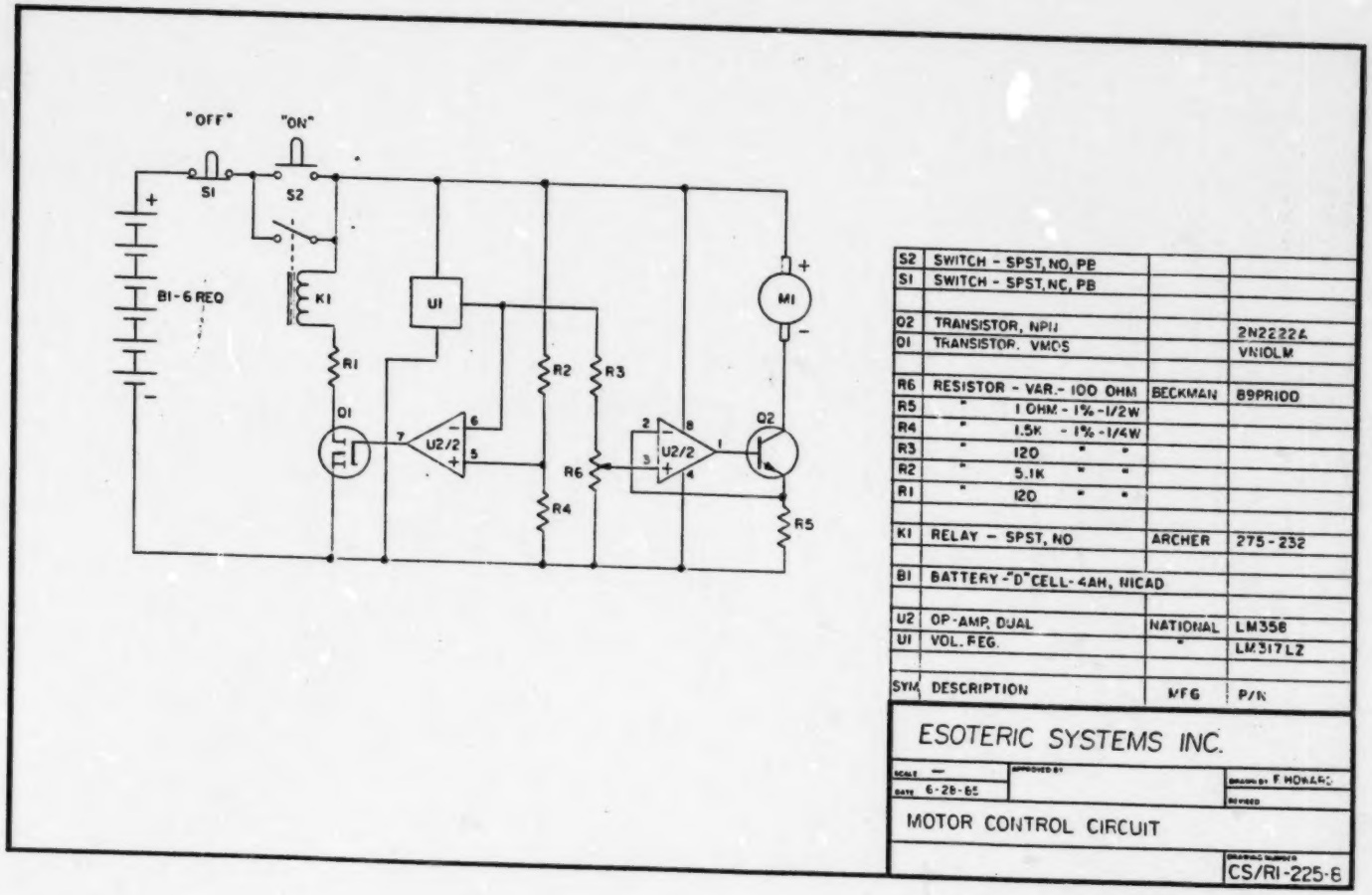


Figure 2. Pump performance profile as a function of operating time. (Measured with fixed orifice - 11.0 in H_2O at 7 lpm)



SYM	DESCRIPTION	MFG	P/N
S2	SWITCH - SPST, NO, PB		
S1	SWITCH - SPST, NC, PB		
Q2	TRANSISTOR, NPN		2N2222A
Q1	TRANSISTOR, VMOS		VN10LM
R6	RESISTOR - VAR. - 100 OHM	BECKMAN	89PR100
R5	" 1 OHM - 1% - 1/2W		
R4	" 1.5K - 1% - 1/4W		
R3	" 120 " "		
R2	" 5.1K " "		
R1	" 120 " "		
K1	RELAY - SPST, NO	ARCHER	275-232
B1	BATTERY - "D" CELL - 4AH, NICAD		
U2	OP-AMP, DUAL	NATIONAL	LM358
U1	VOL. REG.	"	LM317LZ

ESOTERIC SYSTEMS INC.

DATE 6-28-85 — DRAWN BY F. HOWARD

MOTOR CONTROL CIRCUIT

CS/RI-225-6

Figure 3. Motor control circuit diagram.

TABLE 1. NBS SAMPLER OPERATING CHARACTERISTICS

Date	Time, Hr. PDT	Battery Voltage, Volts	Sampler Flow Rate, lpm	DP, cm H_2O[a]
05/27/85	1000	8.25	6.0	8.8
	1030	8.05	6.0	8.8
	1100	7.94	6.0	8.8
	1200	7.77	6.0	8.9
	1400	7.58	6.0	8.9
	1500	7.56	6.0	9.1
	1600	7.52	6.0	9.1
	1700	7.51	6.0	9.1
	1800	7.50	6.0	9.1
05/28/85	0800	7.27	6.0	9.1
	0900	7.21	6.0	9.1
	1000	5.89	6.0	9.1
	1015	5.89	6.0	9.7
	1030	5.89	6.0	9.7
	1045	5.89	6.0	9.7
	1100	5.89	6.0	9.7
	1130	5.87	6.0	9.7
	1200	5.85	6.0	9.7
	1300	5.71	6.0	9.7
	1330	5.38	6.0	9.7
	1345	5.20	6.0	9.7
	1400	4.92	5.7	9.9
	1402	Auto-shutdown		

[a] Differential pressure between backside of filters and atmosphere.

difficult. An additional problem is the possibility that the filter holder, which is held together by friction fit, may become accidentally disassembled during sampling if jarred or bumped e.g. when worn as a personal sampler. A new filter holder was designed for the sampler to eliminate the potential problems associated with the Millipore devices. A diagram of the filter holder assembly is shown in Figure 4. The holder accepts two serially loaded 37mm filters contained in conventional Sierra-Andersen dichotomous sampler cassettes. The cassettes provide a convenient means of handling the filters in the field.

Inlet

A discrepancy was found between the critical dimensions of the 10 μm cut-point inlet reported by NBS (3,4) and those measured on two units supplied to EPA by NBS. It was subsequently learned that one of the dimensions reported by NBS was in error (8). The proper critical dimensions for the PM_{10} inlet are shown in Figure 5. The dimensions of the sampler evaluated in this study conformed to those shown in the figure.

Our investigation of the inlet design has revealed that the funnel insert and the oil-soaked frit may move or become displaced, thereby changing the inlet cut point. Both components are held in place by a friction fit. A means of positively retaining these components in place should be incorporated as a future modification.

HARVARD SAMPLER

A modification was made in the filter holders used in the Harvard sampler evaluated in this study. As received from the manufacturer, the sampler is equipped to use Beckman 5.08 x 5.08 cm filter trays. The filter tray accepts a specially cut 41mm Teflon filter. Upon examination, it appeared that there was potential for misalignment or improper installation of the Beckman filter holder which would result in leakage. Therefore, the base of the sampler housing was modified to accept a 37mm filter retained in a Sierra-Andersen filter cassette. Figure 6 shows the sampler base before and after modification. This modification

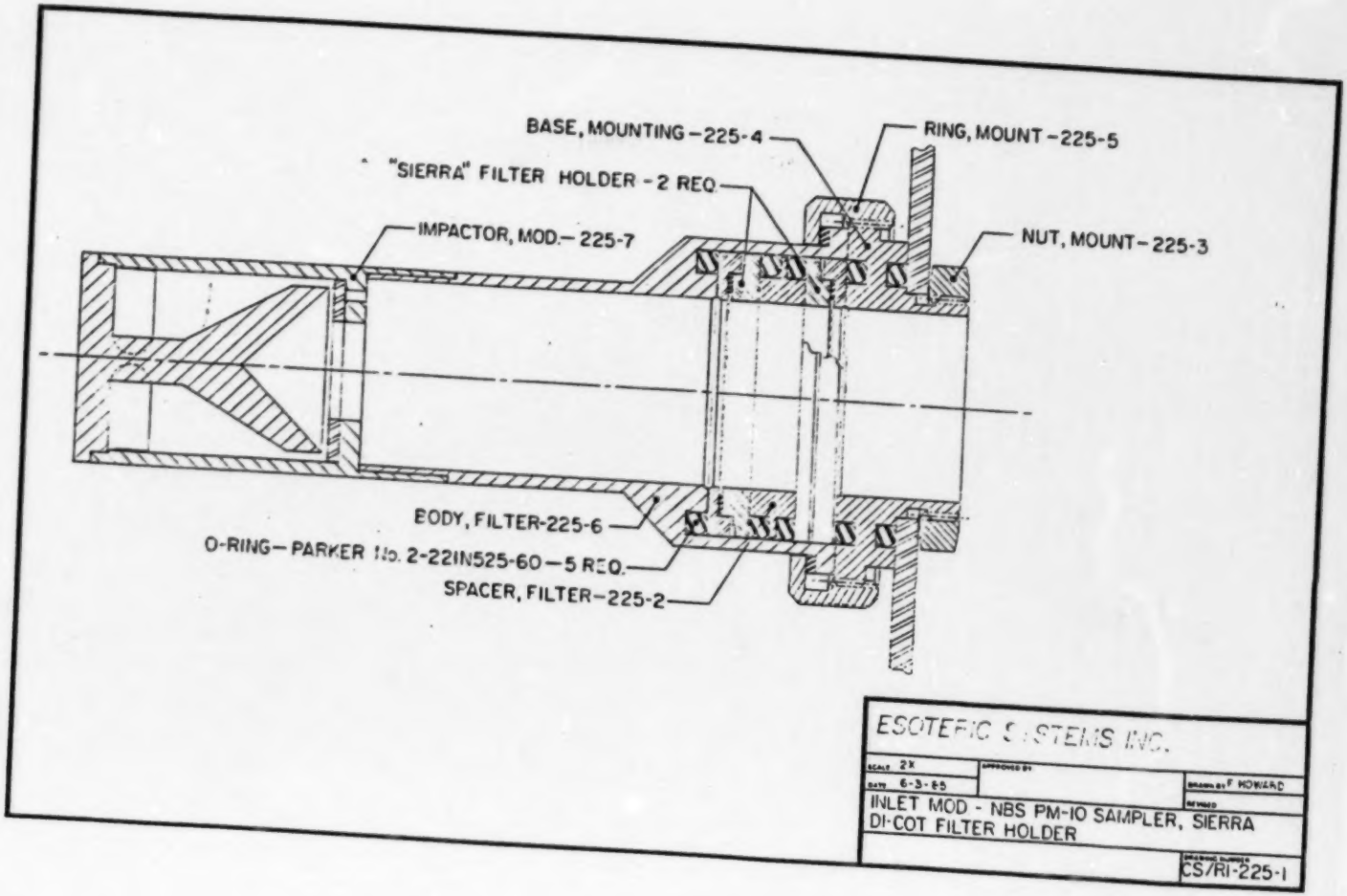

BASE, MOUNTING – 225-4
RING, MOUNT – 225-5
"SIERRA" FILTER HOLDER - 2 REQ.
IMPACTOR, MOD. – 225-7
NUT, MOUNT – 225-3
BODY, FILTER-225-6
O-RING – PARKER No. 2-221N525-60 – 5 REQ.
SPACER, FILTER – 225-2
ESOTERIC SYSTEMS INC.
SCALE 2X
DATE 6-3-85
DRAWN BY F. HOWARD
INLET MOD - NBS PM-10 SAMPLER, SIERRA DI-COT FILTER HOLDER
CS/RI-225-1

Figure 4. Diagram of modified filter holder.

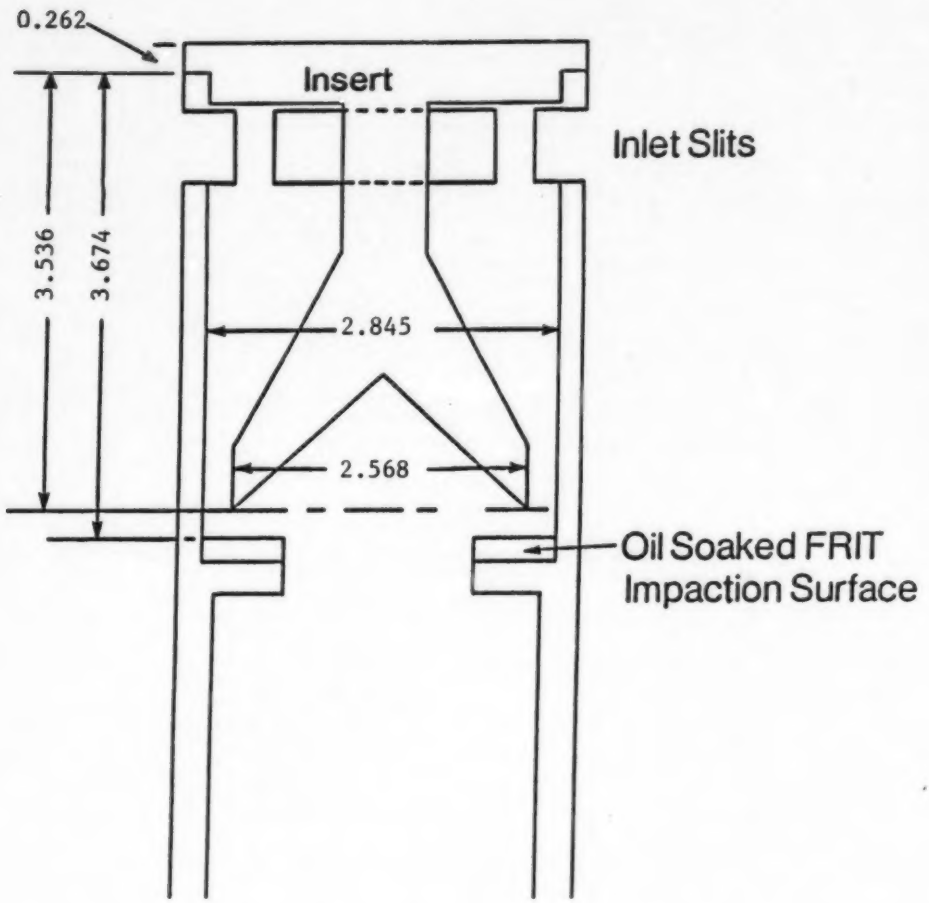


Figure 5. Critical dimensions of NBS 10μm inlet used in this study (values reported in centimeters).

Top of Photo - As supplied by manufacturer; uses Beckman filter tray
Bottom of Photo - Modified to use Sierra-Andersen filter cassette.

Figure 6. Base of Harvard indoor air sampler showing filter holder modification.

provides for fool-proof positioning and alignment of the filter and eliminates the potential for leakage around the filter holder.

SECTION 5

SAMPLER PERFORMANCE EVALUATION

For the evaluation of the NBS and the Harvard samplers, indoor particulate levels were measured concurrently by collocated pairs of the NBS, the Harvard, and the Sierra-Andersen Model 244 Dichotomous (DCT) samplers. The paired measurements provided data to evaluate the precision of measurements made with each sampler, the accuracy of the NBS and Harvard samplers, and the homogeniety of particulate matter in the test atmosphere. The dichotomous sampler, which has well characterized particle collection performance, provided the reference data against which the NBS and Harvard samplers were compared. Duplicate measurements were performed to obtain a measure of the precision of each sampling method. The precision of the reference method is good indicator of the homogeneity of the particle levels in the room. That is, it indicates whether the difference between the other samplers is a true difference rather than due to inhomogeneous particle levels.

APPARATUS

Samplers

The particle samplers used for this experiment were,

(a) the Sierra-Andersen Model 244 dichotomous sampler with a 10 μm cut-point Sierra-Andersen inlet;

(b) the Harvard Indoor Air Sampler, and

(c) a modified version of the NBS Portable Ambient Particulate Sampler.

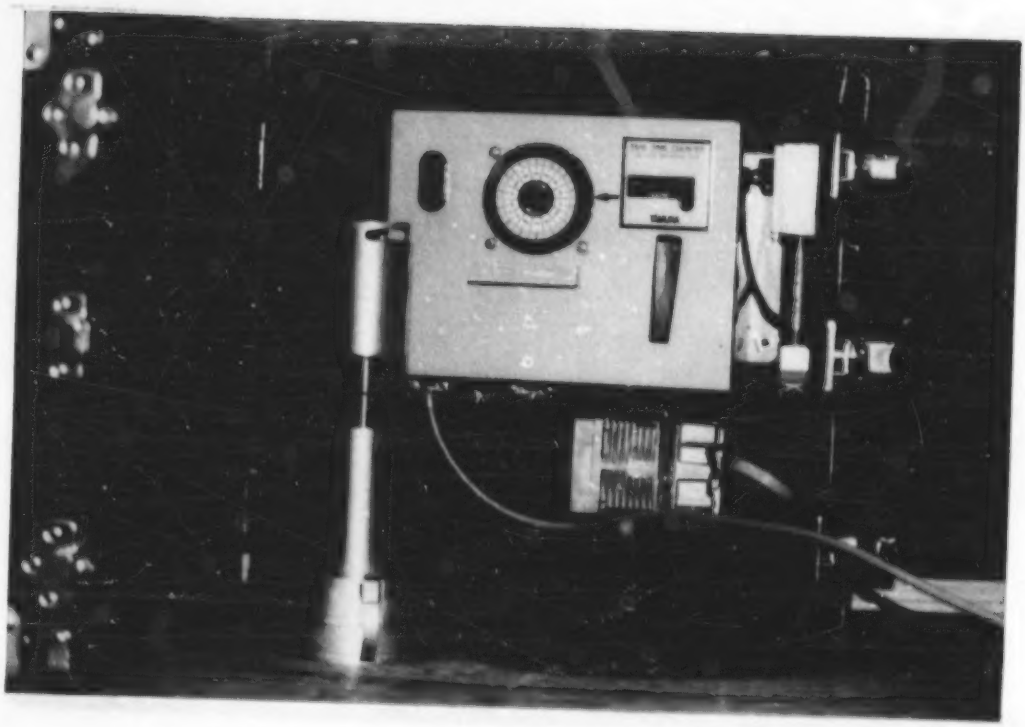
The Sierra-Andersen sampler was used as the reference instrument for the experiments described here. This instrument is widely used for ambient sampling (3). The sampler is used with a size selective inlet, 10 μm in this case, so that only the sub 10 μm particles are sampled. This sub 10 μm sample is further

separated into fine (<2.5 μm) and coarse (2.5 to 10 μm) fractions by a virtual impactor. The two fractions are collected on 37mm Teflon filters (2 μm porosity size) for weighing and further analysis.

The Harvard Indoor Air Sampler shown in Figure 7 is designed for monitoring indoor areas. The unit weighs approximately 9.5 Kg and operates on 110 V power. The sampler head (8.9 cm diameter base x 24 cm high) has a sampling inlet, an impactor for size selective sampling, and a filter holder for sample collection. The sampling head is connected by a flexible line to the pump/timer assemble which is contained in a case approximately 33 x 33 x 25 cm in size. The device is fully described in User Manual supplied with the sampler and by Turner et. al. (7,8). The inlet provides for collection of a representative air sample and size selection is achieved by a user-selected virtual impactor. Impactors with both a 2.5 or a 10 μm cut-size are supplied with the sampler. The 10 μm impactor was used in these experiments. Teflon filters (2 μm porosity size) were used for sample collection. Two virtual impactors of the same cut-size (10 μm) are used in series to minimize errors due to particle bounce, particularly for high mass loadings.

The modified NBS sampler used in these experiments is shown in Figure 8. A description of the modifications made to the NBS prototype is provided in Section 4. The sampling head of the NBS unit contains an impactor which determines the upper limit of the particles size being collected. The dimensions of the impactor used in these experiments were selected to provide a 10 μm cutpoint. Particulate matter that passes through the impactor is further separated into fractions larger and smaller than approximately 3 μm by a 8 μm porosity Nuclepore filter (9). The fine or sub-3 μm fraction is collected on a Teflon filter (37mm, 3 μm porosity size). Other details of the sampler design and performance are given by Fletcher and Bright (3,4).

The original filter holders of both the Harvard and the NBS samplers were replaced by modified filter holders. The latter provided better hermetic sealing and were designed to accept the same filter size and type as those used in the



Foreground: Sampling head (inlet and filter)
Background: Box containing pump and timer

Figure 7. Harvard indoor sampler.

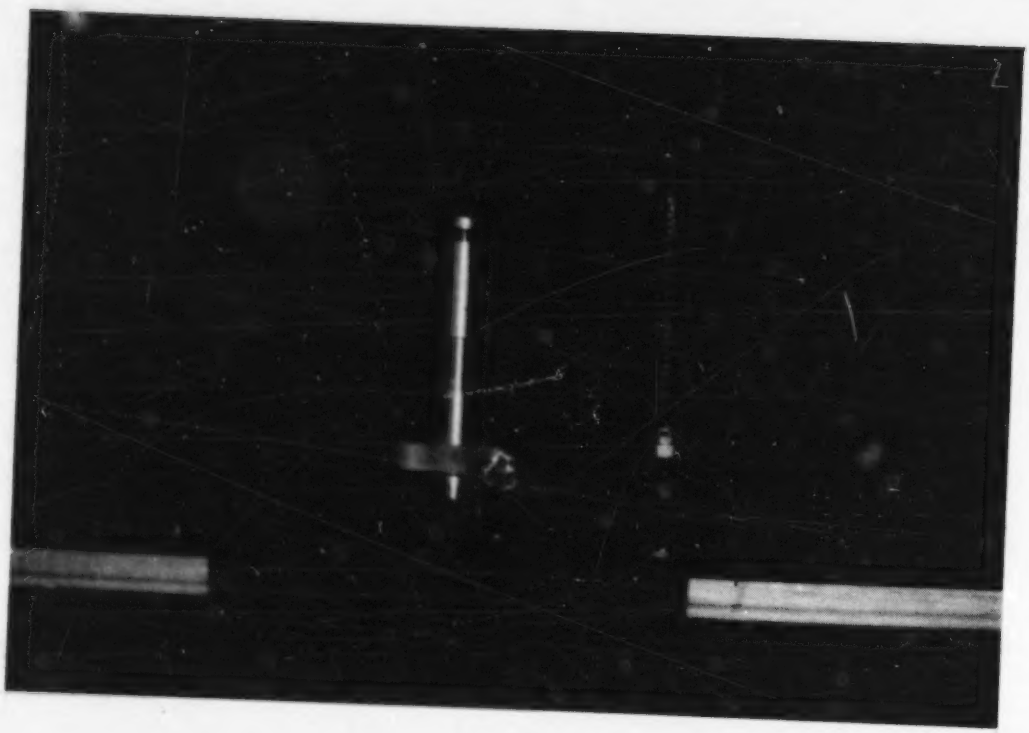


Figure 8. Modified NBS sampler.

Sierra-Andersen dichotomous sampler. Details of the modified filter holders are shown in Figures 4 and 6.

SAMPLER LOCATION/POSITIONING

The experiment was conducted in a 5.5 x 4.3 meter (approx) laboratory room with a 2.4 meter high ceiling. The samplers were arranged in the middle of the room and at the corners of an imaginary hexagon of approximately 1 meter on each side. The samplers were arranged so that no two adjacent units were the same type, i.e., going in sequence around the hexagon the samplers were NBS, Harvard, DCT, NBS, Harvard, DCT. The sampler inlets were elevated approximately 1.5 m from the floor, the height of the dichotomous sampler inlet.

During the sampling experiments, access to the room was restricted to minimize air current that would create particle inhomogeneity. Likewise, ventilation ducts to the room were sealed during the experiments. The pump units of the dichotomous samples were located outside the room in which the sampling was performed.

FLOW CALIBRATIONS

The size and mass of particles collected by each type of sampler used in the study are determined by the air sampling rate. Accordingly, each sampler was calibrated periodically throughout the experiments to ensure operation within the design flow rate range. Flow calibrations of the rotameters on the Sierra-Andersen DCT and NBS samplers were performed before and after the series of sampling experiments. The rotameters were calibrated at several settings (three or more) around the operating set points with a Tylan mass flow meter. The mass flow meter was calibrated prior to the experiments with a NBS-traceable Brooks positive displacement volumeter. The difference in flow rate based on the pre- and post- experiment calibration of the Sierra-Andersen and NBS sampler rotameters was less than five percent. Observations of the rotameter reading on the Sierra-Andersen and NBS samplers before, during, and at the end of each sampling period indicated that flow rate variations were less than five percent

(except when failure of the NBS pumps occurred).

The Harvard sampler is designed to operate at 4 lpm. Accordingly, its flow was adjusted to 4 lpm using the Tylan mass flow meter. The flows were checked before and after each sampling period and no appreciable variation (<5 percent) was observed.

FILTER WEIGHING AND HANDLING

The weight of particulate collected by the three samplers was determined by gravimetric analysis of the filters on a Cahn 26 microbalance. The filters were first inspected for imperfection and the defective filters rejected. The filters were then conditioned for at least 24 hours in a special weighing room where the humidity was maintained between 45-55 percent and the temperature between 20-22^{o}C. The conditioned filters were then consecutively numbered and the tare weights were obtained.

After sampling, the filters were again conditioned for 24 hours at controlled humidity and temperature and their final weights determined. The difference between the two weights (tare and final) is the mass of the particulate matter collected on a filter.

For quality control, 10 percent of all filters were reweighed independently by a second operator. At least every tenth filter in the consecutive sequence of filters was usually selected for quality control. If these weights were within 5 µg of the initial weighings, the weights were accepted. If not, the zero of the balance was reset and recalibrated and all filters within unacceptable control limits reweighed. The quality control procedures were also repeated for the final weight determinations. To ensure that this quality control procedure was effective, the filters were weighed in nominally the same numerical order even after sampling. Filters themselves were selected at random for sampling and were not weighed until the experiments were completed.

In addition, a conditioned blank filter was repeatedly weighed every 10 filter weighings. If the weight of this blank filter was not within 5 μg of its initial weight, the 10 preceding filters were reweighed after zero adjustment and calibration of the balance.

SAMPLING PROCEDURES

Indoor air was sampled by pairs of the three types of samplers as described previously. The sampling periods were nominally 24 hours in duration although one test was extended to ~60 hours. The number of the filter used in a specific sampler in each experiment as well as post measurement flow checks were recorded along with flow settings of the various samplers. To minimize disturbances to the indoor air, the sampler pumps were located outside the room, and, for the same reasons, entry into the room was restricted except for start up and shut down of each experiment.

The NBS sampler is designed to be a portable sampler and its pump is powered by a rechargeable battery pack. It was not feasible to locate this pump outside the room. To expedite the experiments, the NBS sampler was run off an external battery pack. Two battery packs were alternated for each of the sampler so that while one was in operation the other was being recharged.

RESULTS

The indoor particulate concentrations measured by the pairs of the three types of samplers during the study are summarized in Table 2. Nine experiments were run, each lasting approximately 24 hours. One run (#4) was continued beyond 24 hours to obtain higher filter loading. The NBS sampler was operated for the last 5 runs only.

Results in $\mu g/m^3$ (25°C, 760 mm Hg) are presented for fine and coarse fractions and the total particulate matter (PM_{10}) collected by the Sierra-Andersen and NBS samplers. The Harvard sampler yields data only for the total PM_{10} size fraction.

TABLE 2. RESULTS OF COLLOCATED SAMPLING EXPERIMENTS

Run No.	Sampling Duration, Hrs.	Sampler	Mass Concentration ($\mu g/m^3$) Measured with Samplers						
			DCT (c)			NBS			Harvard
			Fine	Coarse	Total	Fine	Coarse	Total	Total
1	24.1	A	10.3	0.6	10.9				8.5
		B	9.0	0.9	9.9				11.6
2	25.1	A	13.7	0.8	14.5				14.2
		B	12.5	0.7	13.2				13.8
3	23.7	A	11.2	0.8	12.0	(a)	(a)	(a)	11.4
		B	10.6	1.3	11.9				12.7
4	60.8	A	9.6	0.5	10.1				10.1
		B	9.3	0.6	9.9				10.2
5	21.0	A	13.7	0.2	13.9	14.0	2.3	16.3	14.7
		B	13.1	0.7	13.8	12.6	2.9	15.5	10.9
6	24.4	A	14.4	0.1	14.5	8.2	2.4	10.6	14.0
		B	13.4	0.4	13.8	8.6	2.4	11.0	13.9
7	23.0	A	9.1	0.0	9.1	6.5	1.9	8.4	8.6
		B	8.5	0.2	8.7	6.6	1.1	7.7	9.1
8	23.3	A	8.9	0.3	9.2	(b)	(b)	(b)	9.5
		B	7.8	0.3	8.1	6.4	2.5	8.9	10.3
9	23.0	A	8.0	0.3	8.3	4.0	1.4	5.4	6.5
		B	8.0	0.5	8.5	(b)	(b)	(b)	7.8

a) Sampler was not operated during these tests
b) Data void due to pump motor failure
c) Dichotomous sampler data are corrected for the mass of fine particulate matter collected on the coarse filter.

The precision of measurements obtained by each type of sampler is quite good. Generally, paired measurements of the PM_{10} mass concentration obtained for each sampler type agree within 10 percent. The agreement of the duplicate determinations demonstrates that the precision associated with measurements made with the samplers is satisfactory and that the particle concentrations in the test environment were relatively homogeneous.

The concentrations measured by the NBS and the Harvard samplers are compared with the dichotomous measurements in Figures 9, 10, and 11. Figure 9 shows that, in general, the concentrations measured by the three instruments agree within about 6 $\mu g/m^3$. Figures 10 and 11 show the Harvard and NBS results plotted against the Sierra-Andersen dichotomous sampler data. The least squares analysis parameters given in Figure 10 show approximately a 1:1 correspondence between the Harvard and dichotomous data. Less agreement is shown between the NBS and dichotomous measurements (Figure 11). However, the latter analysis is based on only five data points. The Harvard sampler data, on the average, agrees within 2 percent of the dichotomous sampler. On the average, the NBS and dichotomous measurements differ by about 9 percent. The mean concentrations measured during the experiments were 11.1 $\mu g/m^3$ (SD=2.3) by the dichotomous sampler; 10.5 $\mu g/m^3$ (SD=3.8) by the NBS sampler; and 11.0 $\mu g/m^3$ (SD=2.5) by the Harvard sampler. Thus, although the individual measurements by the three instruments are subtantially different, the mean concentrations are within the one standard deviation of each other. Due to the small number of data points, particularly for the NBS sampler, more elaborate statistical analyses were not attempted.

The cut size for the fine particle fraction is 2.5 μm for the dichotomous sampler and is reported to be between 2.5 and 3.5 μm for the NBS sampler (3). Thus, for practical purposes, the two instruments can be assumed to sample similar fine and coarse fractions. Comparing the data for the two size fractions, the agreement between the two instruments is very poor. The coarse fraction measured by the NBS sampler is consistently higher than that measured by the Sierra-Andersen dichotomous sampler. The disagreement in the results casts

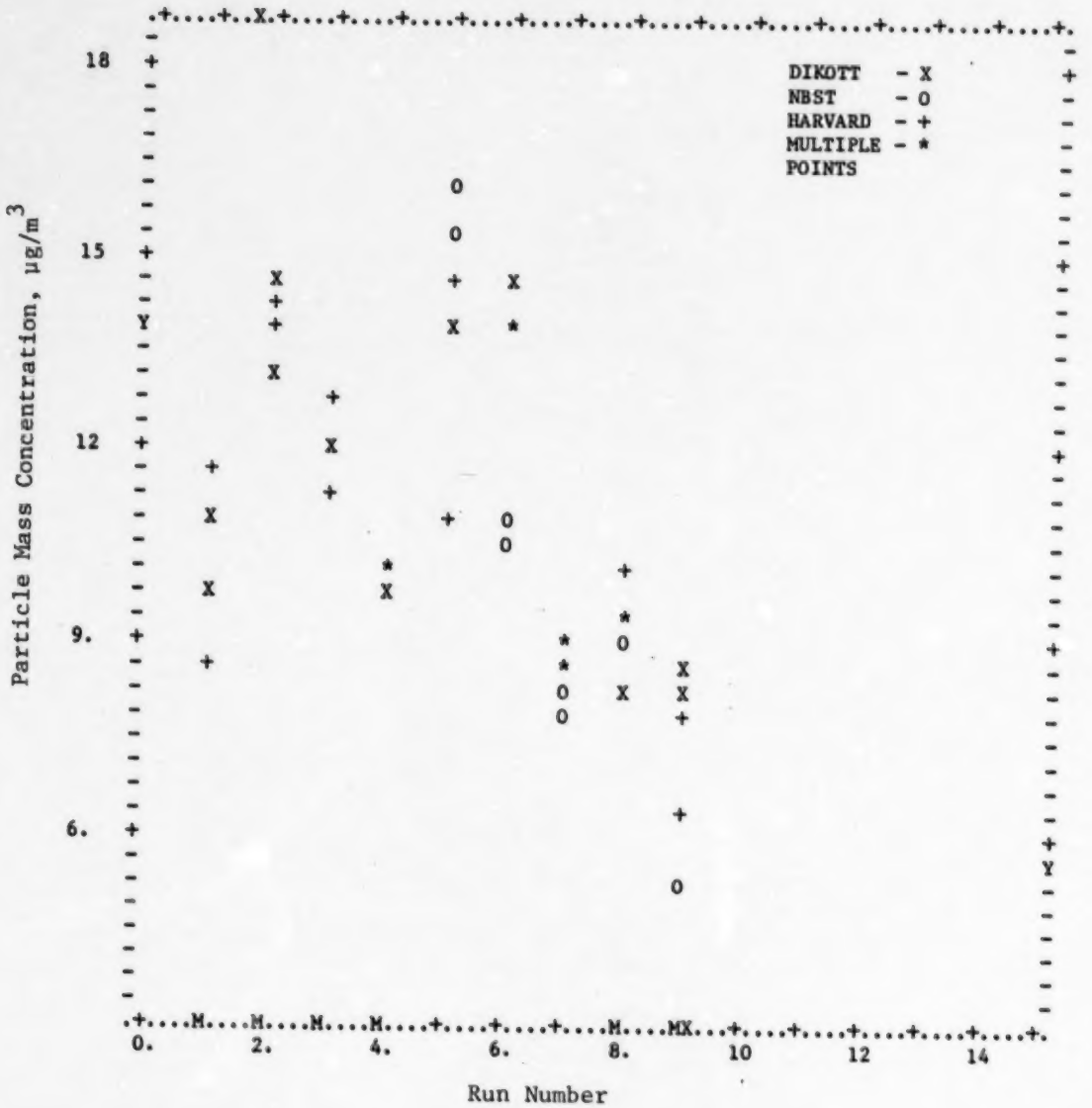


Figure 9. Sampler comparison data.

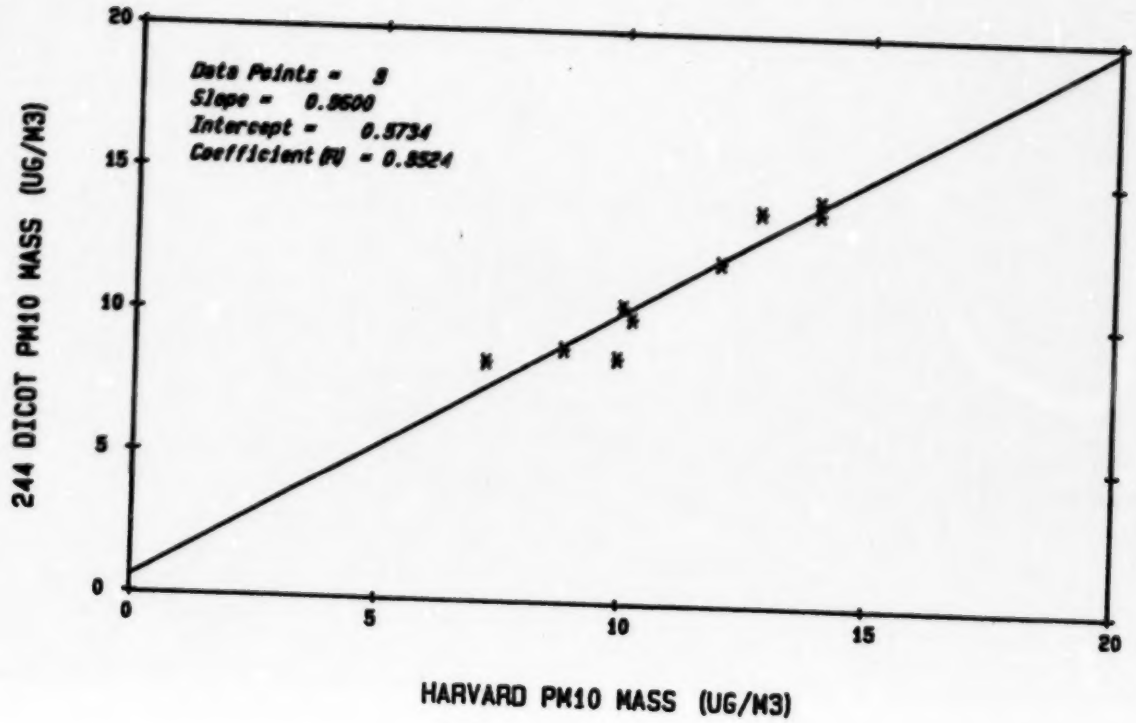


Figure 10. Plot shows least squares analysis of Harvard and dichotomous sampler PM_{10} mass data

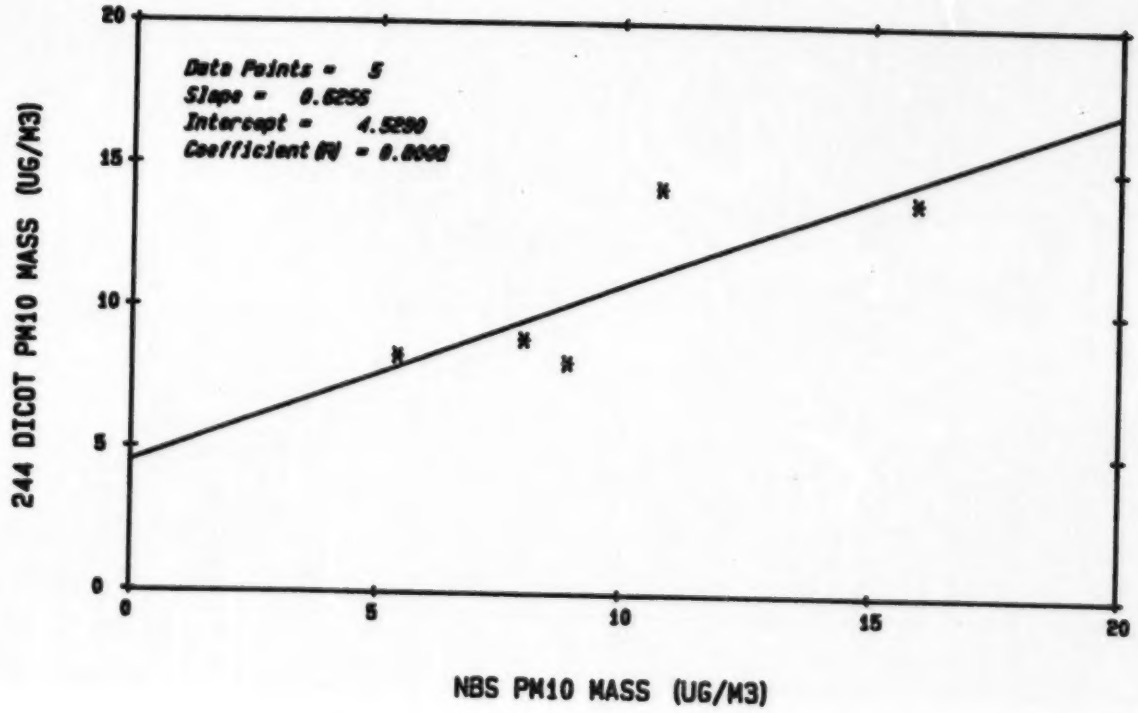


Figure 11. Plot showing least squares analysis of NBS and dichotomous sampler PM_{10} mass data

doubt on the ability of the NBS filter pack to accurately resolve the particle size fractions. John, et. al. have pointed out the limitations of such filter packs for particle sizing.

In summary, the results of a limited number of experiments indicate that the indoor particle concentrations measured by the Harvard sampler and the dichotomous sampler are in close agreement, at least in the low mass concentration range. Although the NBS and dichotomous sampler measurements exhibit a wider difference, the difference is within the spread in the data indicated by the standard deviation. The performance of both the NBS and Harvard samplers should be evaluated under a wider mass concentration range and under a wider variety of environmental conditions.

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